

**EMISSIONS FROM SNOWMOBILE ENGINES USING  
BIO-BASED FUELS AND LUBRICANTS**

**By**

**Jeff J. White  
James N. Carroll**

**FINAL REPORT**

**Prepared for**

**State of Montana Department of Environmental Quality  
P.O. Box 200901  
Helena, Montana 59620-0901**

**October 1998**

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## GLOSSARY

|                 |   |
|-----------------|---|
| Alkylate        | Brand name of aliphatic fuel provided by Aspen Petroleum    |
| CO              | Carbon monoxide   |
| CO <sub>2</sub> | Carbon dioxide  |
| DEQ             | Department of Environmental Quality (Montana)               |
| EEE Clear       | Certification-grade gasoline                                |
| EIS             | Environmental Impact Statement                              |
| FID             | Flame ionization detector                                   |
| Gasohol         | 10% volume ethanol splash-blended in certification gasoline |
| GC              | Gas chromatograph   |
| GC/MS           | Gas chromatograph/mass spectrograph                         |
| HC              | Hydrocarbon   |
| MIR             | Maximum incremental reactivity                              |
| NO <sub>x</sub> | Oxides of nitrogen  |
| NPS             | National Park Service                                       |
| PAH             | Polycyclic aromatic hydrocarbons                            |
| PIB             | Polyisobutylene   |
| PM              | Particulate matter  |
| PUF             | Polyurethane foam   |
| RRF             | Relative response factor                                    |
| SAE             | Society of Automotive Engineers                             |
| SCFM            | Standard cubic feet per minute                              |
| SCMM            | Standard cubic meters per minute                            |
| SIR             | Selected ion recording                                      |
| SO <sub>2</sub> | Sulfur dioxide  |
| THC             | Total hydrocarbons  |
| WOT             | Wide open throttle  |
| YNP             | Yellowstone National Park                                   |



## EXECUTIVE SUMMARY

Snowmobile engine emissions are of concern in environmentally sensitive areas, such as Yellowstone National Park (YNP). A program was undertaken to determine potential emission benefits of use of bio-based fuels and lubricants in snowmobile engines. Candidate fuels and lubricants were evaluated using a fan-cooled 488-cc Polaris engine, and a liquid-cooled 440-cc Arctic Cat engine. Fuels tested include a reference gasoline, gasohol (10% ethanol), and an aliphatic gasoline. Carburetor jets were not changed between fuels. Lubricants evaluated include a bio-based lubricant, a fully synthetic lubricant, a high polyisobutylene (PIB) lubricant, as well as a conventional, mineral-based lubricant. Emissions and fuel consumption were measured using a five-mode test cycle that was developed from analysis of snowmobile field operating data. Emissions measured include total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), carbon dioxide (CO<sub>2</sub>), particulate matter (PM), polycyclic aromatic hydrocarbons (PAH, both particulate bound and vapor-phase), individual hydrocarbon species (C<sub>1</sub>-C<sub>12</sub> and C<sub>13</sub> - C<sub>22</sub>), ammonia, and sulfur dioxide.

The following observations were made:

- Gasohol produced 16 percent less HC, 9 percent less CO, and 24 percent less PM emissions compared to gasoline with the fan-cooled engine. NO<sub>x</sub> emissions were slightly increased, and engine power was about the same.
- The liquid-cooled engine was less sensitive to fuel differences than the fan-cooled engine. With gasohol, CO and PM were reduced 6 percent and 3 percent, respectively, compared to gasoline. Oxides of nitrogen emissions increased 6 percent, and HC emissions increased 5 percent. PM emissions were more than double those of the fan-cooled engine.
- Proper engine setup for temperature and elevation is important. HC, CO, and PM emissions were all significantly increased by richer operation resulting from incorrect setup.

- Lubricant formulation affects PM emission rates. The high PIB TORCO Smoke-less lubricant created significantly less PM than the three other lubricants tested.
- Particulate emission levels are influenced by lubrication rate, and may also be influenced by engine cooling system design. The fan-cooled engine had significantly higher spark plug seat temperatures (and, by inference, cylinder temperatures), and substantially lower PM emissions, than the liquid-cooled engine.
- The aliphatic fuel, while increasing total hydrocarbon emissions, yielded the lowest ozone formation potential of the three fuels tested. It also yielded the lowest benzene emissions.
- Toxic hydrocarbon species are present in snowmobile exhaust in proportions similar to those observed from other sources such as passenger cars fueled with gasoline.

Results show that moderate reductions in emissions can be achieved in the near term through the use of gasohol and low PM lubricants. Subsequent to this project, gasohol was used extensively in snowmobiles in the YNP area during the winter of 1997/8. Both National Park Service and rental sleds operated out of West Yellowstone, Montana were fueled with gasohol. The visible haze associated with snowmobile operation in congested areas was reportedly reduced compared to the previous winter. Operators reported excellent service with gasohol noting equivalent performance, and reduced engine maintenance. No fuel freeze ups were reported. Further studies of snowmobile particulate matter emissions and in-field emissions are planned for late 1998.

## I. INTRODUCTION

Government officials in the Yellowstone National Park region face concerns about health and environmental impacts of emissions from winter transportation, especially snowmobiles operating in stagnant air conditions. Snowmobiles are powered by 2-stroke engines that have high emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM), compared to 4-stroke engines.(1) A partnership of public, private, national, and local organizations developed this study to quantify impacts, and determine how they might be reduced with commercially-available products. Benefits observed in the laboratory study were demonstrated in and around Yellowstone National Park in the winter of 1997/8. These results will help set policy on the fuel, lubricant, and type of equipment that should be operated in Yellowstone, as well as in other environmentally-sensitive areas such as national parks and forests.

\*Numbers in parentheses designate references at end of report.

## II. DESCRIPTION OF PROGRAM

### A. Test Engines

Designated fuels and lubricants were tested with two engines to evaluate emission effects with both air- and water-cooled designs. Engines were selected that were considered most representative of the snowmobile population in the Yellowstone area. According to a usage survey conducted by the State of Montana Department of Environmental Quality, Polaris and Arctic Cat snowmobiles accounted for approximately 81 percent of the 1,400-sled rental fleet in West Yellowstone, Montana (1995/6 season), and the Polaris 488-cc fan-cooled engine was the engine most used in YNP.(2) Engines used were new, and were broken-in according to manufacturer specifications. Engines are described in Table 1.

**TABLE 1. DESCRIPTION OF TEST ENGINES**

|                         |                 |               |
|-------------------------|-----------------|---------------|
| Snowmobile Manufacturer | Polaris         | Arctic Cat    |
| Snowmobile Model        | 1997 Indy Trail | 1995 Panther  |
| Engine Manufacturer     | Fuji HI         | Suzuki        |
| Engine Model            | EC50PM04        | H44-690033    |
| Operating Cycle         | 2-stroke        | 2-stroke      |
| Displacement, cc        | 488             | 440           |
| Cylinders               | 2               | 2             |
| Cooling                 | Fan Air         | Liquid        |
| Carburetion             | 2-Mikuni VM3455 | 2-Mikuni VM34 |
| Main Jet Size           | 210             | 240           |
| Ignition System         | CDI             | CDI           |
| Spark Plug              | BPR8ES          | BPR9ES        |
| Lubrication             | Oil injection   | Oil injection |

Both engines are carbureted and employ oil injection. Lubrication is provided by a crankshaft-driven pump at a rate that is a function of engine speed and throttle position. Mode 1, wide-open-throttle (WOT) observed power was 45 kW at 7000 rpm for the Polaris, and 42 kW at 8000 rpm for the Arctic Cat.

## **B. Test Program**

The test program was designed to evaluate the effects of alternative, bio-based fuels and lubricants on snowmobile engine emissions, power, and fuel consumption. Fuels evaluated included a reference, certification-grade gasoline (EEE Clear), gasohol, which was 10 volume percent ethanol splash-blended with the reference gasoline, and an aliphatic fuel ("Alkylate") purchased from Aspen Petroleum.

Oxygenated fuels have been determined to provide significant reductions in ambient carbon monoxide (CO) concentrations in cities participating in the oxyfuel program.(3) Missoula, Montana has reduced measured ambient CO by 24.3 percent, on average, since introducing oxygenated fuels.(4) Even greater reductions were observed during stagnant air conditions. Gasohol was included in this program to determine whether similar emission reductions could be achieved with snowmobile engines.

Aliphatic fuels have minimal amounts of olefinic and aromatic hydrocarbons, and are used in specialized applications where concern exists about the toxicity of benzene in conventional gasolines. Aliphatic fuels have been found to substantially reduce the ozone formation potential of exhaust organics from both 2- and 4-stroke small engines.(5,6) Alkylate was included in this program to evaluate this benefit in snowmobile engines. Fuel inspection data are presented in Table 2.

Because fuel and lubricant are combusted together in conventional 2-stroke engines, lubricants contribute to engine emissions. An aerosol of uncombusted lubricant is the primary source of 2-stroke engine particulate emissions, as measured gravimetrically from diluted exhaust gas. Lubricants would also be expected to contribute to heavier exhaust hydrocarbons in both liquid and vapor phases.

**TABLE 2. TEST FUEL PROPERTIES**

| <b>Fuel Property</b>   | <b>Method</b>          | <b>Reference Gasoline</b> | <b>Gasohol</b> | <b>Aliphatic Gasoline</b> |
|------------------------|------------------------|---------------------------|----------------|---------------------------|
| Specific Gravity       | ASTM D-4052            | 0.7433                    | 0.7485         | 0.6961                    |
| RVP, psi               | ASTM D-5191            | 8.88                      | 9.69           | 9.36                      |
| Aromatics              | ASTM D-1319<br>(Total) | 27.3                      | 25.7           | 1.6                       |
| Olefins                |                        | 0.6                       | 0.5            | 0.2                       |
| Saturates              |                        | 72.1                      | 64.8           | 98.2                      |
| Carbon, wt. %          | ASTM D-5291            | 86.39                     | 83.11          | 83.89                     |
| Hydrogen, wt. %        |                        | 12.92                     | 13.19          | 16.10                     |
| EtOH, vol. %           | ASTM D-4815            | N/A                       | 9.31           | N/A                       |
| Oxygen, wt. %          |                        | N/A                       | 3.43           | N/A                       |
| Sulfur, wt. %          | ASTM D-2622            | 0.001                     | 0.001          | 0.001                     |
| Benzene, vol. %        | ASTM D-3606            | 0.14                      | 0.11           | 0.00                      |
| Lead, g/gal U.S.       | ASTM D-3237            | <0.001                    | <0.001         | <0.001                    |
| Phosphorus, g/gal U.S. | ASTM D-3231            | <0.001                    | <0.001         | <0.001                    |
| RON                    | SwRI                   | 97.5                      | 101.7          | 96.4                      |
| MON                    | SwRI                   | 89.6                      | 90.6           | 94.6                      |
| Distillation, °C       | ASTM D-86              |                           |                |                           |
| IBP                    |                        | 31                        | 35             | 32                        |
| 5%                     |                        | 42                        | 47             | 48                        |
| 10%                    |                        | 50                        | 52             | 66                        |
| 20%                    |                        | 65                        | 58             | 91                        |
| 50%                    |                        | 105                       | 99             | 104                       |
| 80%                    |                        | 124                       | 124            | 110                       |
| 90%                    |                        | 152                       | 156            | 122                       |
| 95%                    |                        | 172                       | 171            | 143                       |
| EP                     |                        | 199                       | 198            | 194                       |
| Recovery, %            |                        | 97.5                      | 98.0           | 96.0                      |
| Residue, %             |                        | 0.5                       | 0.5            | 1.0                       |
| Loss, %                |                        | 2.0                       | 1.5            | 3.0                       |

Lubricants evaluated included a baseline, mineral-based lubricant (ARCTIC Extreme), as well as three alternative lubricants, CONOCO Biosynthetic, CASTROL XPS, and TORCO Smoke-less. The CONOCO Biosynthetic is a biomass-based, 100 percent synthetic, highly biodegradable lubricant. The CASTROL XPS is a fully synthetic, low-ash 2-stroke lubricant that the manufacturer claims is highly biodegradable as measured by EC standard CEC-L-33A94. The TORCO Smoke-less material is a high PIB (~38% polyisobutylene) content lubricant that is not biodegradable. Lubricant analyses are shown in Table 3. Copies of lubricant container label information are included in Appendix A.

**TABLE 3. LABORATORY ANALYSIS OF LUBRICANTS**

| Property               | Method      | ARCTIC Extreme | CONOCO Biosynthetic | CASTROL XPS | TORCO Smoke-less |
|------------------------|-------------|----------------|---------------------|-------------|------------------|
| Specific Gravity       | ASTM D-4052 | 0.8676         | 0.9265              | 0.8958      | 0.8598           |
| Viscosity @ 40°C, cSt  | ASTM D-445  | 24.16          | 55.62               | 41.23       | 43.24            |
| Viscosity @ 100°C, cSt | ASTM D-445  | 5.01           | 9.05                | 8.78        | 7.22             |
| Flash Point, °C        | ASTM D-92   | 80             | 244                 | 104         | 80               |
| Total Base Number      | ASTM D-4739 | 6.40           | 1.18                | 2.99        | 0.86             |
| Total Acid Number      | ASTM D-664  | 0.71           | 0.68                | 0.64        | 0.25             |
| Carbon, wt. %          | ASTM D-5291 | 84.88          | 75.52               | 80.32       | 85.76            |
| Hydrogen, wt. %        |             | 13.63          | 12.13               | 12.86       | 14.14            |
| Nitrogen, wt. %        | ASTM D-5291 | 0.620          | 0.245               | 0.253       | 0.034            |
| Ba, ppm                |             | <1             | 1                   | 2           | <1               |
| Ca, ppm                |             | 7              | 2                   | 588         | 304              |
| Mg, ppm                |             | <1             | <1                  | 4           | 8                |
| Mn, ppm                |             | <1             | <1                  | <1          | <1               |
| Na, ppm                |             | 4              | 3                   | 1           | 10               |
| P, ppm                 |             | 3              | 186                 | 68          | 9                |
| Zn, ppm                |             | 3              | 1                   | 1           | 9                |
| Distillation by GC, °C |             |                |                     |             |                  |
| IBP                    | ASTM D-2887 | 141            | 318                 | 174         | 140              |
| 5%                     |             | 189            | 400                 | 194         | 184              |
| 10%                    |             | 211            | 469                 | 207         | 210              |
| 20%                    |             | 250            | 484                 | 431         | 250              |
| 50%                    |             | 410            | 492                 | 561         | 418              |
| 80%                    |             | 521            | 605                 | 581         | 641              |
| 90%                    |             | 648            | 618                 | 640         | 684              |
| 95%                    |             | 691            | 692                 | 673         | 698              |

|     |  |     |     |     |     |
|-----|--|-----|-----|-----|-----|
| FBP |  | 724 | 728 | 727 | 724 |
|-----|--|-----|-----|-----|-----|



The test matrix is shown in Table 4. Most tests used a 5-mode snowmobile engine test cycle developed for the International Snowmobile Manufacturers Association (ISMA) by Southwest Research Institute (SwRI). The development of this test cycle is reported in an SAE paper which was presented in Milwaukee, WI in September 1998.(7)

**TABLE 4. TEST MATRIX**

| Test ID                                | Fuel          | Lubricant            |
|--|---------------|----------------------|
| <b>Polaris Fan-Cooled Engine</b>       |               |                      |
| A11-3                                  | Ref. Gasoline | ARCTIC Extreme       |
| A11-4                                  | Ref. Gasoline | ARCTIC Extreme       |
| A12                                    | Ref. Gasoline | CONOCO Bio-Synthetic |
| RICH                                   | Ref. Gasoline | ARCTIC Extreme       |
| A21                                    | Gasohol       | ARCTIC Extreme       |
| A22-1                                  | Gasohol       | CONOCO Bio-Synthetic |
| A31-1                                  | Aliphatic     | ARCTIC Extreme       |
| A31-2                                  | Aliphatic     | ARCTIC Extreme       |
| A22-2                                  | Gasohol       | CONOCO Bio-Synthetic |
| A23                                    | Gasohol       | CASTROL XPS          |
| A24                                    | Gasohol       | TORCO Smoke-less     |
| <b>Arctic Cat Liquid-Cooled Engine</b> |               |                      |
| W11-1                                  | Ref. Gasoline | ARCTIC Extreme       |
| W11-2                                  | Ref. Gasoline | ARCTIC Extreme       |
| W21                                    | Gasohol       | ARCTIC Extreme       |

Tests A11-3 and -4 established baseline emissions on the Polaris engine with reference gasoline and a typical mineral-based lubricant (ARCTIC Extreme), which was approved by Polaris for use in this test. Test A12 evaluated the CONOCO Biosynthetic lubricant with reference gasoline. The RICH test was run with a size 240 jet (210 jet used in other tests), to examine changes in emissions due to richer operation. This test simulates the situation one would have if a snowmobile jetted for lower altitude operation were run at a higher altitude (lower air density), resulting in richer operation. This provides a rough indication of the emissions increases which could result from operating a lower altitude sled in YNP, which has roadside elevations ranging

from 5,300 to 8,800 feet. Tests A21 and A22-1 evaluated emissions with gasohol and two different lubricants. Tests A31-1 and -2 were run with the aliphatic fuel and reference lubricant. Tests A22-2, A23, and A24 were back-to-back, mode-1-only tests of the three alternative lubricants with the lowest emissions fuel (gasohol). Tests W11-1 and -2 and W21 repeated selected combinations on the Arctic Cat liquid-cooled engine.

### **C. Emissions Measurement**

A wide range of emissions measurements were made to thoroughly characterize fuel and lubricant effects. Total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), particulate matter (PM), and carbon dioxide (CO<sub>2</sub>) were measured from diluted exhaust in every test. Instrumentation used included a heated flame ionization detector (HFID) for THC, non-dispersive infrared analyzers for CO and CO<sub>2</sub>, and a chemiluminescent analyzer for NO<sub>x</sub>. Particulate was measured using 90-mm Pallflex filtration of double-diluted exhaust gas following 40 CFR Part 86, Subpart N protocols.

Hydrocarbon speciation was also performed on selected proportional bag samples of diluted exhaust using the Phase I Auto/Oil procedure, which quantifies C<sub>1</sub> to C<sub>12</sub> hydrocarbons, including aldehydes, ketones, and alcohols.

Speciation of higher molecular weight hydrocarbons (C<sub>13</sub>-C<sub>22</sub>) was performed on selected tests using a GC/MS procedure developed for diesel hydrocarbon speciation.

Particulate phase polycyclic aromatic hydrocarbons (PAH) were determined on selected tests by analysis of extracts of particulate collected on 20x20-inch Pallflex filters. Gas phase PAH compounds were determined from samples collected on polyurethane foam (PUF) traps. PAH species were identified and quantified using a quadrupole GC/MS operated in selected ion recording mode.

Ammonia and sulfur dioxide emissions were determined in selected tests. Sulfur dioxide emissions (SO<sub>2</sub>) were calculated based on analyzed fuel and lubricant sulfur levels and measured consumption rates. Ammonia levels were determined by bubbling samples of diluted exhaust through impingers containing 0.1N sulfuric acid. The resulting ammonium salt was quantified using an ion chromatograph fitted with a conductivity detector.

#### **D. Test Procedure**

Emissions were measured using a 5-mode steady-state snowmobile engine test cycle that was developed for ISMA by SwRI.(7) Real time operating data were collected on four instrumented snowmobiles operated over various on- and off-trail segments representing five driving styles. These data were statistically analyzed to determine steady-state modes representative of real in-use operation. This cycle is described in Table 5.

**Table 5. Snowmobile Engine Test Cycle**

| <b>Mode</b>   | <b>1</b> | <b>2</b> | <b>3</b> | <b>4</b> | <b>5</b> |
|---------------|----------|----------|----------|----------|----------|
| Speed, %      | 100      | 85       | 75       | 65       | Idle     |
| Torque, %     | 100      | 51       | 33       | 19       | 0        |
| Wt. Factor, % | 12       | 27       | 25       | 31       | 5        |

Modes are run in order from highest to lowest speed. One hundred percent engine speed is the speed declared by the snowmobile manufacturer as representative of the maximum steady engine speed in snowmobile operation. Torque values are specified as a percent of the maximum (WOT) torque observed at 100 percent speed in Mode 1.

#### **E. Test Facility**

Snowmobile engines were tested in SwRI's nonroad engine test cell. Each engine was mounted on a bed plate using jack stands, and connected to a dynamometer using an appropriate coupling. A high speed, water-brake dynamometer was used for the Polaris engine. The Arctic Cat engine was tested with an eddy-current dynamometer using a toothed-belt speed reduction system. Engines were instrumented for measurement of various temperatures and pressures. Fuel and lubricant consumption were determined as mass delivered from precision balances. The Polaris engine is shown in Figure 1.

Engines were operated using stock intake air boxes and exhaust systems to ensure correct operation. All engine exhaust was collected without physical connection to the exhaust system, and conveyed to a 0.457 m (18 in) diameter dilution tunnel. Total dilute flow was maintained at approximately 16.0 scmm (565 scfm). Proportional bag samples of diluted exhaust were collected for THC, CO, NO<sub>x</sub>, and CO<sub>2</sub> analysis and HC speciation. A portion of the diluted exhaust stream was further diluted in a secondary dilution tunnel for particulate measurement, as shown in Figure 2.

### III. RESULTS AND DISCUSSION

#### A. Criteria Pollutants

Five-mode cycle emissions and fuel consumption for the Polaris engine are shown in Table 6 and in Figures 3, 4, and 5. HC, CO, and PM emissions are high, and NO<sub>x</sub> emissions are low, as is typical of 2-stroke engines. Emissions are comparable to previously reported results with allowance for differences in engine operation and test procedure.(1,8) Detailed emission test results are included in Appendix B.

The RICH test generated significantly higher HC, CO, and PM emissions (20%, 14%, and 28%, respectively) than the mean gasoline baseline result. Fuel consumption also increased by 13 percent, and Mode 1 (WOT) power decreased by 14 percent. This test was run with a richer-than- specification main jet to simulate the effect of operating a snowmobile at a higher altitude than originally calibrated for. The difference between the normal (210) and richer (240) jet corresponds roughly to an 1800 m (5906 ft) altitude difference, and confirms that incorrect jetting significantly increases snowmobile engine emissions.

Test A12 examined emissions with the CONOCO Biosynthetic lubricant and reference gasoline. Results were similar to those generated with the reference lubricant (ARCTIC Extreme), except for particulate matter, which increased 66 percent. This may be related to the lower front end volatility of the CONOCO lubricant compared to the reference lubricant, as observed in the distillation results in Table 3.

The gasohol results indicate substantial emission benefits may be obtained using an oxygenated fuel in snowmobiles. Test A21 (gasohol with reference lubricant) produced 16 percent less HC, nine percent less CO, and 24 percent less PM than the mean gasoline baseline result. Specific fuel consumption was also reduced, and Mode 1 power was maintained or possibly slightly increased, from base gasoline levels. The gasohol test run with the CONOCO lubricant (A22-1) resulted in 64 percent more PM than Test A21 with the reference lubricant, confirming the increased PM observed in Test A12. The gasohol/CONOCO test also produced less HC and CO than the gasohol/ARCTIC Extreme test, however it is unlikely that this was due to a lubricant change. HC and CO reductions were not observed in the gasoline-

based comparison between these lubricants, and it is more likely that these emissions differences reflect engine drift between tests.

One mechanism by which gasohol reduces emissions is by enleanment due to the fuel's oxygen content. It is possible that enleanment from rejetting the carburetors could provide similar emission reductions with gasoline. It would be worthwhile to perform such a comparison in a future study.

Aliphatic fuel results reflected increased HC and PM results (33% and 47%, respectively), compared to the mean gasoline baseline result. Fuel consumption also increased, and Mode 1 power was reduced about 5 percent. Combustion quality was worse than with either gasoline or gasohol, as evidenced by increased frequency of audible misfire.

Engine emissions were not as repeatable as we would have liked. Steep engine power output characteristics, coupled with the less precise control of the waterbrake dynamometer made it difficult to achieve precise control of modal setpoints. To try to obtain a more accurate comparison of lubricant effects, three lubricants were run back-to-back in Mode 1 (WOT) operation without shutting the engine off or making any adjustments. After switching lubricants, the engine was operated for a sufficient length of time to flush the injection system with the new lubricant prior to taking emission data. Gasohol was selected as the fuel for this comparison because it provided lower emissions than the reference gasoline. Results are summarized in Table 7, and compared with those with ARCTIC Extreme in Figure 6.

**TABLE 7. POLARIS ENGINE--MODE 1 LUBRICANT EMISSION RESULTS**

| Fuel           | Lubricant | Test ID | Mode 1 Emissions, g/kW-h |      |                   |      |
|----------------|-----------|---------|--------------------------|------|-------------------|------|
|                |           |         | BSHC                     | BSCO | BSNO <sub>x</sub> | BSPM |
| Gasohol        | CASTROL   | A23     | 91                       | 387  | 0.74              | 0.21 |
| Gasohol        | TORCO     | A24     | 97                       | 381  | 0.80              | 0.12 |
| Gasohol        | CONOCO    | A22-2   | 91                       | 372  | 0.83              | 0.64 |
| TORCO/CASTROL  |           |         | 108%                     | 98%  | 109%              | 57%  |
| CONOCO/CASTROL |           |         | 101%                     | 96%  | 112%              | 310% |

Differences in HC, CO, and NO<sub>x</sub> emissions are small, and likely not significant. These results are consistent with 5-mode results which showed significantly higher PM emissions with the CONOCO lubricant. As a point of reference, Mode 1 PM emissions in the gasohol/ARCTIC Extreme test (A21) were 0.27 g/kW-h, similar to results observed with the CASTROL lubricant. The TORCO Smoke-less lubricant emitted 43 percent less PM than the CASTROL, which suggests that the use of this material could decrease the visible haze associated with snowmobile engine operation.

Five-mode cycle test results with the Arctic Cat engine are presented in Table 8. To obtain better engine control, an eddy-current dynamometer, fitted with a belt-driven speed reduction system, was used for this engine (see Figure 7). This approach provided much better control than the water-brake dynamometer used with the Polaris engine. Speed and load setpoints were maintained typically within a few percent of set value. In spite of this, variability between repeat Arctic Cat tests W11-1 and -2 was not substantially better compared to Polaris results. This may be due to the type of carburetion employed with these engines, which uses three different circuits to control fuel delivery. Emission rates appear to be highly sensitive to small changes in engine operation, particularly at the more heavily weighted part-throttle modes. Additional work would be required to better identify and control the sources of variability in snowmobile engine emission results. This was also noted during test cycle validation round-robin testing conducted by the snowmobile industry.(7)

**TABLE 8. ARCTIC CAT ENGINE--5-MODE CYCLE EMISSION TEST RESULTS**

| Fuel                     | Lubricant | Test ID | Emissions, g/kW-h |      |                   |      | BSFC, kg/kW-h | Mode 1 kW |
|--------------------------|-----------|---------|-------------------|------|-------------------|------|---------------|-----------|
|                          |           |         | BSHC              | BSCO | BSNO <sub>x</sub> | BSPM |               |           |
| Gasoline                 | ARCTIC    | W11-1   | 191               | 468  | 0.68              | 4.14 | 0.64          | 42.5      |
| Gasoline                 | ARCTIC    | W11-2   | 227               | 505  | 0.64              | 5.11 | 0.69          | 42.3      |
| Baseline Gasoline (mean) |           |         | 209               | 487  | 0.66              | 4.63 | 0.67          | 42.4      |
| Gasohol                  | ARCTIC    | W21     | 220               | 459  | 0.70              | 4.51 | 0.69          | 43.0      |
| Gasohol/Gasoline         |           |         | 105%              | 94%  | 106%              | 97%  | 103%          | 101%      |

The liquid-cooled Arctic Cat engine was less sensitive to fuel differences than the Polaris engine. With gasohol, CO and PM were reduced 6 percent and 3 percent, respectively. Oxides of nitrogen emissions increased 6 percent, and HC emissions increased 5 percent. Mode 1 WOT power with gasohol was equivalent to or slightly greater than with gasoline.

Emission rates of HC, CO, and NO<sub>x</sub> were similar for the two engines tested. Particulate emission rates, however, were much higher with the Arctic Cat engine as shown in Figure 8. An examination of lubrication rates (fuel/oil ratio) (Table 9) showed that the Arctic Cat engine ran 3 to 18 percent more oil-rich than the Polaris engine, except in Mode 5 (idle) where the Arctic Cat engine lubrication rate was over three times that of the Polaris engine. Note that values in Table 9 are for fuel/oil ratio, thus, a lower value indicates a higher lubrication rate. These differences, however, are insufficient to account for the magnitude of the PM difference. Further investigation suggested an additional factor which is shown in Figure 9. Spark plug seat temperature data showed that there were large differences in cylinder temperatures between fan-cooled (Polaris) and liquid-cooled (Arctic Cat) designs. Polaris spark plug seat temperatures were typically 180°C higher in Mode 1 than those with the Arctic Cat engine, and it is likely that these higher cylinder temperatures promote more complete volatilization and combustion of injected lubricant, resulting in lower PM emissions.

**TABLE 9. MEASURED FUEL/OIL RATIO AND SPARK PLUG SEAT TEMPERATURE DATA**

| Engine                                   | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 |
|--|--------|--------|--------|--------|--------|
| <b>Measured Fuel/Oil Ratio</b>           |        |        |        |        |        |
| Polaris                                  | 30     | 43     | 46     | 44     | 90     |
| Arctic Cat                               | 29     | 37     | 38     | 38     | 24     |
| <b>Spark Plug Seat Temperature, °C</b>   |        |        |        |        |        |
| Polaris                                  | 251    | 166    | 139    | 113    | 70     |
| Arctic Cat                               | 71     | 66     | 64     | 60     | 54     |
| Polaris data - mean values of A11-3&4    |        |        |        |        |        |
| Arctic Cat data - mean values of W11-1&2 |        |        |        |        |        |



## **B. Speciated Emissions**

### **1. C<sub>1</sub> - C<sub>12</sub> Speciation**

Hydrocarbon speciation was performed on selected tests using the Phase I Auto/Oil procedure (one GC), which can identify and quantify 223 individual C<sub>1</sub>-C<sub>12</sub> hydrocarbons. Results may be analyzed in a variety of ways depending on specific properties of interest. Organic gases may be classified according to hydrocarbon type, such as paraffin, olefin, aromatic, carbonyl, and other. Toxic or other target species emissions rates can be examined. Since the regulation of organic gas emissions is due to their role in ozone formation, speciation results are often analyzed to determine ozone formation potential, based on application of species-specific Maximum Incremental Reactivity (MIR) values. Selected Polaris engine speciation results are presented in Table 10. Total speciated hydrocarbons are compared to THC levels determined by the flame ionization detector (FID) hydrocarbon analyzer. Agreement between the two methods is quite good, with GC levels ranging from 90 to 101 percent of FID HC levels.

Four organic gases have been classified by EPA as air toxics--1,3-butadiene, benzene, formaldehyde, and acetaldehyde, and these are shown in Table 10 and Figure 10. Emission rates of 1,3-butadiene are fairly similar in all the different fuel/lubricant combinations. Benzene emissions were considerably less with the aliphatic fuel, as would be expected with its low level of aromatics. It appears that some benzene is being produced in the combustion of this aliphatic fuel, perhaps through thermal cracking and reforming. Formaldehyde emissions are slightly higher with both gasohol and aliphatic fuel than with gasoline. Acetaldehyde emissions are also increased with the ethanol-containing fuel, as expected, because the ethyl group is a direct precursor of acetaldehyde, and may be readily converted to acetaldehyde through partial oxidation.

Overall, toxic species appear to be present in similar proportions to those observed from other sources. For example, 1,3-butadiene, benzene, formaldehyde, and acetaldehyde were present in gasoline-fueled Polaris engine exhaust at levels of 0.14, 0.80, 0.64, and 0.10 percent, respectively of total hydrocarbon emissions. These levels are similar, percentage wise, to those observed in older catalyst and non-catalyst equipped passenger cars.(9)

Hydrocarbon and NO<sub>x</sub> emissions are controlled because they participate in ozone formation in the atmosphere in the presence of sunlight. Ozone is a toxic gas which is very dangerous to health. Different HC species have differing atmospheric reactivities, or ozone formation potentials, and thus different fuels may promote higher or lower ozone formation, depending on the emission rates of individual HC species. Ozone formation potential was reduced 16 percent with gasohol, compared to gasoline results. The aliphatic fuel provided an even greater reduction (22%) in spite of its higher *total* hydrocarbon emissions. This is due to the lower composite reactivity of species emitted.

Fuel characteristics may also be viewed in terms of specific reactivity, which is equivalent to total ozone formation potential divided by total hydrocarbon levels. Specific reactivities for gasohol tests were 3 percent higher than with gasoline. With aliphatic fuel, specific reactivity was 25 percent less than with gasoline. These values reflect a slightly higher composite exhaust reactivity with an ethanol-containing fuel, and a significantly lower composite reactivity with the aliphatic fuel. While these data suggest some important benefits of aliphatic fuels, ozone formation potential is likely of less concern than CO (and HC) emissions in a winter-use scenario, because ozone is less likely to be formed at low winter temperatures.

Speciation analysis was also performed on the Mode 1 only comparison of the three lubricants on the Polaris engine. Results are shown in Table 11. In general, emission levels are similar and the differences observed may not be significant.

Selected speciation results for the Arctic Cat engine are presented in Table 12, compared to results using the same fuels and lubricants in the Polaris engine. Toxic species emissions from the Arctic Cat engine were significantly less than from the Polaris engine with both gasoline and gasohol. Both total HC and ozone formation potential were higher with the Arctic Cat engine with gasohol, which may indicate poorer combustion, compared to the Polaris engine.

Figures 11 through 17 present detailed summaries of speciation results in graphical form. Emission rates are plotted on a logarithmic scale versus carbon number. Different classes of compounds are color coded for easier identification. Results from Test A12 (Polaris, gasoline, CONOCO) show few differences compared to baseline result A11-3 (Polaris, gasoline,

ARCTIC Extreme). It appears that a change in lubricant has little effect on emissions of  $C_{12}$  and lower hydrocarbons. The result from Test A21 (Polaris, gasohol, ARCTIC Extreme) has an ethanol peak in the  $C_2$  range, as expected.

Comparing results from Tests A21 and A22-1 (Polaris, gasohol, CONOCO), again little difference is observed in results due to the lubricant change. Test A31-1 (Polaris, aliphatic, ARCTIC Extreme) shows reduced aromatic peaks, as expected with a low aromatic fuel. Test W21 (Arctic Cat, gasohol, ARCTIC Extreme) also displays an ethanol peak. Detailed tabular speciation results are in Appendix C, including a one-spreadsheet summary of weighted total results from all tests.

## 2. $C_{13}$ - $C_{22}$ Speciation

Speciation of higher molecular weight ( $>C_{12}$ ) hydrocarbons was also performed in selected tests. Heated diluted exhaust was drawn through sorbent tubes packed with Tenax GR®, which is a solid sorbent effective at capturing hydrocarbons in this mass range. Tenax GR® is also hydrophobic, which prevents it from being saturated with water vapor from the humid exhaust gas.

The sampling system used is depicted in Figure 18. The temperature of the sampling system up to the sorbent tubes was maintained at 375°F to prevent condensation of analyte molecules. Before reaching the sorbent tubes, the sample passed through heated, flip-top filter holders fitted with glass fiber particulate filters.

For analysis, samples were thermally desorbed onto a 60m long x 0.32 mm diameter, 1 $\mu$ m film DB-1 gas chromatograph column coupled to a quadrupole mass spectrometer (GC/MS). A thermal desorption autosampler was used to heat the sorbent tube to 300°C while the inert carrier gas, helium, purged the sample from the tube. The sample tube was purged onto a 0°C cold trap for 20 minutes where the sample was collected. Next, the cold trap was ballistically heated to 300°C, introducing the sample into the GC column all at once. The mass spectrometer was operated in full scan mode, resulting in spectra that can be compared to a database of over 138,000 reference spectra. A computer algorithm was used to compare the unknown spectra against those in the database, and to rank them as to degree of fit. The final determination of the unknown compound's identity was made by the analyst.

The following species were qualitatively identified in most of the samples.

| COMPOUND                       | COMPOUND                   |
|--------------------------------|----------------------------|
| Trimethyl hexane               | Trimethyl hexane           |
| Ethyl benzene                  | 2,3-dihydro-1H-indene      |
| Dimethyl benzene (xylene)      | Dimethyl ethyl benzene     |
| Ethenyl benzene (styrene)      | Methylethyl methyl benzene |
| Isopropyl benzene (cumene)     | Ethyl dimethyl benzene     |
| Benzaldehyde                   | Undecane                   |
| Propyl benzene                 | Naphthalene                |
| Trimethyl benzene              | Dodecane                   |
| Methyl propyl benzene          | Tridecane                  |
| Isopropyltoluene (para cymene) | Tetradecane                |
| Methylethyl benzene            |                            |

Unfortunately, speciation results were not consistent from test to test. Sampling and analytical techniques for speciation of heavier hydrocarbons were designed for diesel exhaust, and this approach may not be optimal for exhaust from spark-ignited engines. Hydrocarbon concentrations in snowmobile engine exhaust are higher than those of diesel engines by several orders of magnitude. Even with adjustment of sampling volumes and dilution ratios, the high proportions of lighter HCs may have overloaded the traps, limiting collection of higher molecular weight compounds. Further study of the character of heavier hydrocarbons from snowmobiles or other 2-stroke engines will require development and validation of special sampling and analytical techniques.

### **C. Polycyclic Aromatic Hydrocarbon (PAH) Emissions**

Polycyclic aromatic hydrocarbons are of interest because this class of hydrocarbons contains several compounds which have been shown to have carcinogenic or mutagenic effects in animal studies. PAHs were analyzed

from both particulate phase and vapor phase samples. Particulate phase samples were collected from diluted exhaust on 20x20-inch Pallflex filters. Vapor phase samples of diluted exhaust were obtained using XAD-2 resin sandwiched in two pieces of polyurethane foam (PUF). Details of analytical procedures are given below.

Filter media and the XAD-2 resins were extracted with toluene and methylene chloride, respectively, by Soxhlet continuous extraction for 18 hours. The PUFs were extracted with hexane:diethyl ether (94:6, v/v) in the same way for 18 hours. One hundred  $\mu\text{L}$  of a surrogate solution containing 4,4'-dibromobiphenyl, anthracene-d10, and p-terphenyl-d14 at a level of 20 ng/ $\mu\text{L}$  was spiked to the media just prior to extraction, to monitor extraction efficiency. The sample extracts were solvent exchanged into hexane and subjected to a cleanup procedure described in US EPA Method 610. The PUF and XAD-2 resin extracts were combined prior to the cleanup procedure. The final sample extract was brought up to a total volume of 1.0 mL.

Samples were analyzed on a FISON MD800 GC/MS in selected ion recording (SIR) mode. Separation of PAHs was accomplished by injecting a one microliter aliquot of the sample extract onto a 60m DB-5 capillary column. A set of six PAH calibration standards containing target PAHs and deuterated PAHs as internal standards were analyzed. A relative response factor (RRF) for each PAH in relation to a deuterated PAH was established. A linearity criterion of 30% relative standard deviation for the RRFs of each PAH was used as a guideline for a multi-point calibration curve established over the range from 0.01 to 10 ng/ $\mu\text{L}$  (equivalent to 10 to 10,000 total ng/PAH/sample). For PAH quantitation, the same deuterated PAH mixture was spiked into the sample extract at the time of analysis and was used for calculating PAH concentrations. Dilution analyses were performed on samples that had target compounds exceeding the calibration range.

Particulate phase PAH results are shown in Table 13. Emission rates are high, as would be expected from engines with high total hydrocarbon emissions. Results are also shown graphically in Figure 19. Species are plotted from left to right in the same order as in the table. It appears that the Polaris has higher PAH emissions with gasoline than the Arctic Cat engine. PAH emissions with gasohol (A21) were significantly less than with the reference gasoline (A11-3). Mode-one-only data with the three lubricants, with gasohol, shows lower PAH emissions with the CASTROL and TORCO lubricants than with the CONOCO lubricant.

Vapor phase PAH levels were determined in Test A11-3, and these are summarized along with particulate phase results in Table 14 and Figure 20. PAH emissions are present in significant levels in both vapor phase and particulate phase samples. Vapor phase levels are highest for the lower molecular weight compounds, but particulate phase samples still contained significant amounts of the lighter compounds. In terms of total mass emission rate for species measured, the particulate phase samples accounted for 61 percent of the total and the vapor phase for 39%. Detailed PAH results are included in Appendix D.

**TABLE 14. PARTICULATE AND VAPOR PHASE PAH EMISSIONS--TEST A11-3**

| Compound               | Wtd. Total, $\mu\text{g}/\text{kW-hr}$ |             |       |
|------------------------|--|-------------|-------|
|                        | Vapor                                  | Particulate | Total |
|                        | Phase                                  | Phase       | PAH   |
| Naphthalene            | 11                                     | 1           | 11    |
| Acenaphthylene         | 209                                    | 6           | 215   |
| Acenaphthene           | 6                                      | 0           | 7     |
| Fluorene               | 635                                    | 82          | 717   |
| Phenanthrene           | 383                                    | 205         | 588   |
| Anthracene             | 129                                    | 51          | 181   |
| Fluoranthene           | 304                                    | 581         | 886   |
| Pyrene                 | 222                                    | 835         | 1056  |
| Benzo(A)Anthracene     | 9                                      | 114         | 123   |
| Chrysene               | 5                                      | 65          | 71    |
| 1-Nitropyrene          | 1                                      | 3           | 4     |
| Benzo(B)fluoranthene   | 1                                      | 50          | 51    |
| Benzo(K)fluoranthene   | 2                                      | 41          | 43    |
| Benzo(E)pyrene         | 1                                      | 78          | 80    |
| Benzo(A)pyrene         | 2                                      | 109         | 111   |
| Indeno(1,2,3-CD)pyrene | 1                                      | 135         | 137   |
| Dibenz(A,H)anthracene  | 0                                      | 3           | 3     |
| Benzo(G,H,I)perylene   | 5                                      | 597         | 602   |



#### **D. Ammonia Emissions**

Ammonium ion has been detected in several snowpack samples from YNP. Ammonia analysis was performed on selected tests to help determine whether snowmobiles could be a source of these emissions.

Ammonia emissions were determined by bubbling a proportional sample of diluted exhaust through an impinger containing a 0.1 N sulfuric acid solution. The resulting ammonium salt was quantified using an ion chromatograph fitted with a conductivity detector. Results are shown in Table 15. While results show fairly low levels of ammonia being emitted, it is not possible to determine whether ammonium ion in snowpack samples came from snowmobile emissions. Further study would be required to specifically identify the source of the ammonium ion. Detailed ammonia results are in Appendix E.

#### **E. Sulfur Dioxide Emissions**

Sulfur dioxide in engine exhaust may react with moisture in the exhaust or other compounds in the atmosphere to form sulfate emissions. Sulfur dioxide emissions were calculated, based on analyzed fuel and lubricant sulfur levels and measured flowrates. It was assumed that all of the sulfur in the trapped mixture was combusted to SO<sub>2</sub>. Trapping efficiencies were supplied by Polaris, as shown in Table 16, and these values were used for sulfur dioxide emission calculations for both snowmobiles. Results are shown in Table 17. Sulfur dioxide emissions from the snowmobile engines are low due to the low sulfur levels in the fuels.



**TABLE 16. POLARIS ENGINE TRAPPING EFFICIENCIES**

| Mode                   | 1  | 2  | 3  | 4  | 5  |
|------------------------|----|----|----|----|----|
| Trapping Efficiency, % | 83 | 72 | 60 | 49 | 49 |

**TABLE 17. SULFUR DIOXIDE EMISSIONS**

| Test ID |         | Sulfur Dioxide Emissions |        |        |        |        |            |
|---------|---------|--------------------------|--------|--------|--------|--------|------------|
|         |         | Mode 1                   | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Wtd. Total |
| A11-3   | g/hr    | 2.67                     | 1.19   | 0.64   | 0.38   | 0.03   | 0.92       |
|         | g/kw-hr | 0.06                     | 0.06   | 0.06   | 0.07   |        | 0.06       |
| A11-4   | g/hr    | 2.68                     | 1.12   | 0.62   | 0.20   | 0.02   | 0.84       |
|         | g/kw-hr | 0.06                     | 0.06   | 0.05   | 0.04   |        | 0.05       |
| RICH    | g/hr    | 2.69                     | 1.66   | 0.86   | 0.23   | 0.02   | 1.06       |
|         | g/kw-hr | 0.07                     | 0.08   | 0.07   | 0.04   |        | 0.07       |
| A12     | g/hr    | 2.65                     | 1.18   | 0.70   | 0.27   | 0.03   | 0.90       |
|         | g/kw-hr | 0.06                     | 0.06   | 0.06   | 0.05   |        | 0.06       |
| A21     | g/hr    | 2.68                     | 1.04   | 0.59   | 0.27   | 0.03   | 0.83       |
|         | g/kw-hr | 0.06                     | 0.05   | 0.05   | 0.05   |        | 0.05       |
| A22     | g/hr    | 2.65                     | 0.97   | 0.55   | 0.23   | 0.04   | 0.79       |
|         | g/kw-hr | 0.06                     | 0.05   | 0.05   | 0.04   |        | 0.05       |
| A31-1   | g/hr    | 2.54                     | 1.22   | 0.68   | 0.31   | 0.01   | 0.90       |
|         | g/kw-hr | 0.06                     | 0.06   | 0.06   | 0.06   |        | 0.06       |
| A31-2   | g/hr    | *                        | *      | *      | *      | *      | *          |
|         | g/kw-hr | *                        | *      | *      | *      |        | *          |
| W11-1   | g/hr    | 2.75                     | 1.20   | 0.63   | 0.41   | 0.09   | 0.94       |
|         | g/kw-hr | 0.06                     | 0.06   | 0.06   | 0.08   |        | 0.06       |
| W11-2   | g/hr    | 2.74                     | 1.21   | 0.68   | 0.54   | 0.10   | 1.00       |
|         | g/kw-hr | 0.06                     | 0.07   | 0.06   | 0.09   |        | 0.07       |
| W21     | g/hr    | 2.65                     | 1.26   | 0.68   | 0.53   | 0.08   | 1.00       |
|         | g/kw-hr | 0.06                     | 0.07   | 0.06   | 0.10   |        | 0.07       |

\* Oil flow was not measured

## IV. CONCLUSIONS, RECOMMENDATIONS, AND FOLLOW-UP ACTIVITIES

### A. Conclusions

Snowmobiles emit significant amounts of HC, CO, and PM due to the use of 2-stroke engines. Emissions of air toxics are proportionate to HC emission rates. Results show that both type of fuel and lubricant have effects on emissions from snowmobile engines.

- Gasohol reduced CO and PM emissions, and slightly increased NO<sub>x</sub> emissions, while maintaining equivalent engine power, as compared to results with reference gasoline.

Gasohol produced 16 percent less HC, 9 percent less CO, and 24 percent less PM emissions compared to gasoline with the fan-cooled engine. NO<sub>x</sub> emissions were slightly increased, and engine power was about the same.

The liquid-cooled engine was less sensitive to fuel differences than the fan-cooled engine. With gasohol, CO and PM were reduced 6 percent and 3 percent, respectively, compared to gasoline. Oxides of nitrogen emissions increased 6 percent, and HC emissions increased 5 percent. PM emissions were more than double those of the fan-cooled engine.

- Proper engine setup for temperature and elevation is important. HC, CO, and PM emissions were all significantly increased by richer operation resulting from incorrect setup.
- Lubricant formulation affects PM emission rates. The high PIB TORCO Smoke-less lubricant created significantly less PM than the three other lubricants tested.
- Particulate emission levels are influenced by lubrication rate, and may also be influenced by engine cooling system design. The fan-cooled engine had significantly higher spark plug seat temperatures (and, by inference, cylinder temperatures), and substantially lower PM emissions, than the liquid-cooled engine.

- The aliphatic fuel, while increasing total hydrocarbon emissions, yielded the lowest ozone formation potential of the three fuels tested. It also yielded the lowest benzene emissions. While these data suggest some important benefits of aliphatic fuels, ozone formation potential is likely of less concern than CO (and HC) emissions in a winter-use scenario, because ozone is less likely to be formed at low winter temperatures.
- Toxic hydrocarbon species are present in snowmobile exhaust in proportions similar to those observed from other sources such as passenger cars fueled with gasoline.

Moderate emission reductions were observed using alternative fuels and lubricants. While reductions are significant, they are likely not as great as could be achieved with advanced engine technologies such as 4-stroke designs, or direct injected 2-stroke designs. Alternative fuels and lubricants have the advantage of being able to provide near term benefits, as they can be implemented now in the existing snowmobile fleet.

## **B. Recommendations**

While this project generated much good information about snowmobile engine emissions and fuel and lubricant effects, many questions remain unanswered, and other issues have also been surfaced. The following areas are recommended for further study.

1. One mechanism by which alcohol-containing fuels reduce emissions is by enleanment due to the fuel's oxygen content. It may be of interest to compare emission reductions achieved with gasohol to those achieved by an "equivalent" amount of enleanment using conventional gasoline.
2. Emission results were found to be sensitive to engine operating conditions, including intake air temperature and humidity. Further studies should be performed to identify and reduce sources of variability in snowmobile engine emission results.

3. Lubricants evaluated showed large differences in PM emission rates. This suggests that opportunity exists to develop advanced, low PM lubricants for snowmobiles and other 2-stroke powered equipment.
4. During review of the draft report, several individuals questioned the impact of snowmobile operation on water quality. This issue was beyond the scope of this project, but is certainly worthy of investigation.
5. Advanced, low-emission engine designs are being developed for personal watercraft to meet EPA marine engine emission regulations. It may be of interest to evaluate the feasibility and potential emission benefits of utilizing these or other designs in snowmobile engines.
6. Snowmobile PM emissions, while high, are known to be quite different from particulate emitted by diesel engines. Diesel particulate is composed of carbonaceous soot with adsorbed heavy hydrocarbons. Two-stroke PM is primarily uncombusted lubricant. Snowmobile particulate matter should be further studied to quantify its character and any potential health impacts.
7. Speciation of heavier hydrocarbons in snowmobile exhaust was problematic. Sampling procedures and analytical techniques could be refined to provide better results from engines of this type.
8. The question of whether snowmobiles contribute to ammonia found in snowpack was unanswered in this study. Further research would be required to establish a link in this area, and determine whether there are any significant impacts.

### **C. Follow-Up Activities**

Results show that moderate reductions in emissions can be achieved in the near term through the use of gasohol and low PM lubricants. Subsequent to this project, gasohol was used extensively in snowmobiles in the YNP area during the winter of 1997/8. Both National Park Service and rental sleds operated out of West Yellowstone, Montana were fueled with gasohol. The visible haze associated with snowmobile operation in congested areas was

reportedly reduced compared to the previous winter. Operators reported excellent service with gasohol, noting equivalent performance and reduced engine maintenance. No fuel freeze ups were reported. Further studies of snowmobile particulate matter emissions and in-field emissions are planned for late 1998.

As a result of this demonstration, the Park Service at Yellowstone requested its next fuel supply agreement to provide only gasohol in place of gasoline for year-round use (about 220,000 gallons). The contractor was selected through their normal solicitation process, and gasohol (E-10) became the only fuel available for gasoline-powered NPS vehicles in Yellowstone starting June 1, 1998. AmFac, Yellowstone's primary concessionaire, is also planning to use gasohol in its winter fleet. The Yellowstone Park Service Stations (YPSS) are investigating the feasibility of offering gasohol to the public for the 1998/99 winter season.

As noted above, the private sector actively promoted the use of these products through news releases and paid radio announcements. By January 4, 1998, all West Yellowstone snowmobile and snowcoach operators were voluntarily using gasohol and environmentally preferred lubes. All service stations in West Yellowstone carried gasohol. Gasohol also was provided at service stations in Jackson and Cody, Wyoming.

As a result of the laboratory and field work, the Montana DEQ drafted text for a brochure (in Appendix F) on how to make snow machines environmentally friendly. The text was distributed by area snowmobilers to visitors, and has been incorporated with other rules for snowmobiling on their World Wide Web page. The brochure is being printed by Conoco. Polar Bear Productions and Conoco have teamed up to develop a cost-shared program for television that summarizes this work. The program is aimed at snowmobilers visiting in the Yellowstone area, and is planned for airing in the 1998/9 season.

A series of eight scientific studies (totaling about \$807,000) was developed to evaluate the questions remaining from these laboratory investigations and field demonstrations. By September 28, 1998, all but two studies had been fully funded as summarized below. This science program for the 1998/99 winter will develop more data on fuels, emissions, economics, and winter use (only \$22,800 of it will be from the Western Regional Bioenergy Program). These studies will be the basis for the Yellowstone

winter use EIS, and the results will be applied over the next 20 or more years.

This project also helped fuel the Green Gateway Corridors Project which promotes safety and the availability of environmentally friendly products at service stations along the highways leading to and from the Park. Conoco stations (and later others) will use environmentally friendly products and practices in the Park gateway corridors (Yellowstone, Grand Teton, Glacier, etc). This project was developed during the Greening of Yellowstone Workshop in May 1998, along with two others that follow.

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| <b>Winter Science Studies: Transportation and Visitation in Yellowstone Region</b>   |  |   |             |
|--|--|---|-------------|
| <b>Study Title</b>   | <b>Principal Investigator</b>  | <b>Resource studied and need</b>  | <b>Cost</b> |
| 1. *Characteristics of Snowmobile Particulate Emissions with bio-based lube  | Southwest Research Institute   | Particulate emissions: determine size, chemistry, diesel comparison & tradeoffs   | \$39,500    |
| 2. ****Field Studies of Aerosol Formation and Biodegradation of Snowmobile Fuels, Lubricants and Emissions in the Yellowstone Region | Drs Bonnie Tyler, Richard Peterson, Montana State University                                 | Define benefits & applicable stds for biodegradable, non-toxic cold climate fuels, lubes. Air vs water quality benefits               | \$87,191    |
| 3. *Measurement and Bioassay of Airborne Toxics and Regulated Pollutants from Snowmobiles  | Drs N Kado, Paul Kuzmicky, University of California, Davis                                   | Emissions and select air toxics in conjunction with reported health effects in park service personnel (OSHA)                          | \$183,000   |
| 4. ***Snowmobile Emissions: (in-field measurement of) the effects of ethanol-based fuels   | Drs Stedman, Gary Bishop, University of Denver   | Develop and demonstrate a lowcost field method to (IR) monitor criteria emissions   | \$45,600    |
| 5. *Snowpack and snowmelt runoff chemical analysis, YNP and Montana  | Dr George Ingersoll, U. S. Geological Survey   | Relationship between trail use, major ions & metals, in snowpack and spring runoff  | \$54,560    |
| 6. **Field Evaluation of Gasohol's Ability to Reduce Snowmobiler Exposure to CO in Yellowstone                                       | Dr L Fussel  | Statistically valid exposure levels of CO and select emissions for ethanol-blends for high, medium- low- trail use                    | \$135,320   |
| 7. *Social Carrying Capacity of YNP for Winter Use   | Drs William Borrie, Wayne Freimund, University of Montana, Dr Robert Mannin, Univ of Vermont | Social indicators of carrying capacity of visitors (visitor concerns about emissions, congestion) and reductions in travel congestion | \$62,000    |
| 8. Air Quality Monitoring,   | MT DEQ, YDEQ, NPS  | PM-10, CO   | \$200,000   |
| Total Costs  |  |   | \$807,171   |
| *Pew Charitable Trusts   |  |   | \$160,000   |
| **Interscan Foundation   |  |   | \$58,660    |
| ***Remote Sensing Technologies Inc West Yellowstone, ISMA, and DOE WRBEP   |  |   | \$46,190    |
| ****DEQ, DuPont, Conoco, NSF   |  |   | \$246,191   |
| National Park Service  |  |   | \$180,000   |
| Total unfunded (Projects 2 and 3)  |  |   | \$116,130   |



## REFERENCES

1. White, J.J., Carroll, J.N., Lourenco, J.G., and Downing-Iaali, A., "Baseline and Controlled Exhaust Emissions From Off-Highway Vehicle Engines," SAE Paper 931541, Pisa, Italy, December 1993.
2. State of Montana Department of Environmental Quality telephone survey, letter to Jeff White from Howard Haines, May 8, 1996.
3. "Regression Modeling of Oxyfuel Effects on Ambient CO Concentrations," Systems Applications International, Inc., January 8, 1997.
4. State of Montana Air Quality Control Implementation Plan, Vol. III, Chapter 32, December 9, 1996.
5. Hare, C.T. and White, J.J., "Toward the Environmentally-Friendly Small Engine: Fuel, Lubricant, and Emission Measurement Issues," JSAE Paper 911222, Yokohama, Japan, October 1991.
6. Hare, C.T. and Carroll, J.N., "Reactivity of Exhaust Emissions From a Small Two-Stroke Engine and a Small Four-Stroke Engine Operating on Gasoline and LPG," SAE Paper 931540, Pisa, Italy, December 1993.
7. Wright, C.W. and White, J.J., "Development and Validation of a Snowmobile Engine Emission Test Procedure," SAE Paper 982017, Milwaukee, Wisconsin, September 1998.
8. Hare, C.T. and Springer, K.J., "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Final Report - Part 7, Snowmobiles," by Southwest Research Institute under Contract EHC 70-108 to U.S. EPA, April 1974.
9. Warner-Selph, M.A., and Smith, L.R., "Assessment of Unregulated Emissions from Gasoline Oxygenated Blends," Final Report EPA 460/3-91-002 to EPA, Contract No. 68-C9-0004, March 1991.

## **APPENDIX F**

### **PROJECT SUMMARY SHEET**

**Pacific Northwest and Alaska  
Regional Bioenergy Program  
Montana Project Summary**

1. **Title:** *Biomass Alternatives for Snowmobiles: Emissions Testing and Demonstration of Bio-based Options for Emissions Reduction in 2-Stroke Snowmobile Engines in Yellowstone National Park, Snowmobile in the Park*
2. **Brief Description:** This project provides data and a demonstration of bio-based fuel and lube options for reducing potential pollution and health problems caused by snowmobiles in Yellowstone National Park (YNP). Laboratory emissions tests compared the effects on snowmobile emissions of biomass-based fuel and lubrication oils to those emissions from conventional fuel and lubes. A bio-based ethanol blend was used as a fuel. Lubrication oils included animal and plant fats and their derivatives, such as Conoco's Bio-Synthetic 2-Cycle Oil. Products meeting manufacturer's specifications that reduced emissions and health concerns, with increased biodegradability, were later demonstrated in Yellowstone National Park (YNP). Industry representatives and others feel that the project is helping set policy for the use of snowmobiles in Yellowstone and the surrounding public lands. If successful, project results ultimately will reduce pollution without additional regulations, and provide a market for a new value-added industry.
3. **Identification**      Number:      DE-FG51-95R020683,      2ST.104.01  
SNOWSUM.WPD
4. **Contractor/Grantee:** Montana Department of Environmental Quality (DEQ)  
1520 East Sixth Avenue, P. O. Box 200901, Helena, Montana 59620-0901  
**Contact:** Howard E. Haines, Bioenergy Engineering Specialist, Energy Division  
406-444-6773, FAX 406-444-6836, E-mail hhaines@mt.gov
5. **Program Manager:** Jeffrey W. James  
**U. S. Department of Energy Seattle Support Office**

**800 Fifth Avenue, Suite 3950, Seattle, WA 98104  
Phone 206-553-2097, FAX 206-553-1300**

- 6. U. S. Department of Energy Regional Bioenergy Program Funds:**  
(1995) \$ 100,000  
Estimated total cost: \$ 564,000

- 7. Cost Sharing and Project Participants:**
- |  |                    |
|--|--------------------|
| Montana Department Environmental Quality (DEQ)                   | \$ 80,000          |
| Wyoming Department of Commerce, Energy Office                    | \$ 10,000          |
| U. S. DOE Clean Cities Program                                   | \$ 15,000          |
| U.S. Department of the Interior, National Park Service (NPS)     |                    |
| Yellowstone National Park and Air Resources Division             | \$ 100,000         |
| International Snowmobile Manufacturers Association<br>(ISMA)     | \$ 195,000         |
| CONOCO, Inc.   | \$ 27,000          |
| International Association of Snowmobile Administrators<br>(IASA) | \$ 1,000           |
| Montana Snowmobile Association                                   | (Being determined) |
| Renewable Fuels Association                                      | \$ 4,000           |
| Southwest Research Institute                                     | \$ 26,000          |
| Ethanol Producers and Consumers of Montana                       | \$ 3,000           |
| West Yellowstone Chamber of Commerce                             | \$ 3,000           |
| Allen Oil Company  |                    |
- Others participants include:
- Ace Snowmobiles, West Yellowstone
  - Arctco (Arctic Cat)
  - Bombardier Corporation, SeaDoo/SkiDoo Division
  - Castrol Oil Inc. and Rotax Engine
  - Canyon Street Exxon, West Yellowstone
  - Clyde's Service Station, West Yellowstone
  - Oronite Additives, Chevron Inc.
  - Hi Country Snowmobile Rental, West Yellowstone
  - Polaris Industries Inc.
  - Rendezvous Snowmobile Rental, West Yellowstone
  - Three Bears Lodge, West Yellowstone
  - Travelers Service Center & Snowmobile Rental
  - Torco International Corporation
  - Stage Coach Inn, West Yellowstone
  - SnoWest Magazine

West Yellowstone Conference Hotel and Rentals  
Westgate Service Station and Rentals  
Yamaha Motor Corporation, U.S.A.  
Yellowstone Adventures/Ski Doo, West Yellowstone  
Yellowstone Arctic Cat Yamaha, West Yellowstone  
Yellowstone Snowmobiles

**8. Expanded Description:** The goal of this project is to reduce potential health and environmental problems caused by snowmobiles in and around Yellowstone National Park. These problems raise the possibility that snowmobiling in the Park may eventually be regulated or even curtailed in some way. Actions taken by the NPS regarding snowmobiles will have a significant impact on gateway communities. This project has applicability beyond the Yellowstone region for other areas characterized by valley topography and areas with a tendency for winter air inversions. The project is expected to help set public policy for snowmobiles in Yellowstone and Grand Teton national parks, and the seven adjoining national forests. The project may contribute to upcoming rulemaking on snowmobiles by the U.S. Environmental Protection Agency (EPA).

The project first developed emissions and performance data in a laboratory setting at Southwest Research Institute using two common types of snowmobile engines and an industry approved test protocol based on typical U.S. field use. The lab report described the performance, emissions, and air toxics from these engines using both conventional and biomass-based fuel and lubrication oils. An emissions-grade gasoline, EEE Clear, gasohol (a 10 percent blend of bio-based ethanol with gasoline), and an aliphatic gasoline were used as fuels.

Engine lubrication oils examined a representative sample of the 52 commercial formulations that are currently available or may be available soon. Those tested included Arctic Extreme (as the conventional oil), a highly biodegradable oil --Conoco's Bio-Synthetic 2-Cycle Oil (mostly derived from animal and plant fats), a synthetic biodegradable oil with solvent-Castrol's (Rotax XPS) Biodegradable Synthetic Lubrication Oil, and a fully synthetic, petroleum-based, non-biodegradable, low-particulate oil with a high concentration of polyisobutylene (PIB)--Torco Synthetic Smoke-Less 2-Cycle Oil.

Preliminary laboratory findings were shared in a series of meetings between DEQ and ISMA (July 1997), the Idaho Division of Environmental Quality and Idaho Department of Parks and Recreation (July 1997), the Montana Snowmobile Association Board of Directors (September 1997), Minnesota Department of Pollution Control (November 1997), and others. The purpose of the meetings was to better identify the potential user's needs, and to clarify points for the draft report.

Laboratory results indicated products that could potentially be demonstrated in the fleet of 99 National Park Service snowmobiles. The field demonstration by NPS snow machines focused on products that show high biodegradability and efficiency, reduced hazards to health and environment, meet manufacturers specifications, and reduce smoke, odor, and noise. A pilot demonstration was conducted with the 99 NPS snowmobiles during both the 1995-1996 and 1996-1997 seasons using a bio-based lube oil--Conoco's Biosynthetic 2-Cycle Engine Oil. This oil was used, because it meets the NPS criteria of biodegradability, and snowmobile manufacturers requirements. The 1997-1998 snowmobile season demonstrated products screened in the lab testing, which was completed in June 1997. NPS expanded its demonstration to include gasohol.

Data collected during the field demonstrations included fuel and lube oil consumption, mileage, maintenance, and subjective comments of snowmobile operators and Park visitors. Ambient air monitoring and analysis was conducted continuously for particulate matter in West Yellowstone. Ambient air sampling of select pollutants was done the first winter, and again at heavy use periods during the field demonstration. Permanent glacier snowpack was sampled for 40 metallic ions, total organic carbons, sulfates, nitrates, and ammonia left by emissions in 1996 and 1998. The 1998 samples were analyzed for select hydrocarbon species. Both sets of snow samples were collected in trails with heavy, moderate, and light snowmobile use. Samples also were collected 100 meters distant from the trails. (This work is being reported by USGS and NPS in cooperation with DEQ, USFS, and Montana Fish, Wildlife and Parks.) If successful, the project might reduce pollution and help set a fact-based policy on snowmobiles. Success also would allow snowmobilers to operate older machines without undue regulations.

**ABSTRACT:** Snowmobile engine emissions were becoming a health and environmental concern in environmentally sensitive areas, such as Yellowstone National Park (YNP). A program was undertaken to evaluate

potential emission benefits of use of biomass-based fuels and lubricants in snowmobile engines. Candidate fuels and lubricants were evaluated using an air-cooled, 488 cc, carbureted Polaris engine, and a water-cooled, 440 cc Arctic Cat engine. Fuels tested include a reference gasoline (EEE Clear), gasohol (10% ethanol), and an aliphatic gasoline. Lubricants evaluated include two biodegradable lubricants, a high polyisobutylene (PIB) lubricant, and conventional, mineral-based lubricants. Emissions and fuel consumption were measured using a five-mode test cycle that was developed from analysis of snowmobile field operating data. Emissions measured include total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), sulfur oxides (SO<sub>x</sub>), carbon dioxide (CO<sub>2</sub>), particulate matter (PM), polycyclic aromatic hydrocarbons (PAH), vapor-phase PAH, and individual hydrocarbon species (hydrocarbon speciation). Emissions and fuel consumption using bio-based fuels and lubricants are compared to results using conventional fuels and lubricants. Promising candidates were recommended for further study in a field demonstration in Yellowstone National Park.

**9. Needs Addressed:** Officials at Yellowstone National Park have documented health and environmental problems caused by 2-stroke engines in snowmobiles. A large percentage of snowmobile emissions results from unburned fuel and lubrication oil consumed with the fuel (about 3 percent of the fuel is lubrication, and 20 to 33 percent of this fuel is emitted unburned into the atmosphere). Ethanol blends are expected to reduce CO emissions. Data from the European countries shows that commercially available biomass-based lubrication oil can reduce CO, PM, and HC emissions. Some European countries require that 2-stroke engines use an all-alkane (non-aromatic) gasoline for health reasons. Several bio-based lubrication oils and fuels exist in this country and may find a niche market in tourist-related applications.

The project addresses the participants' needs by:

- Developing data to help set public policy
- Analyzing/defining a niche market for agricultural (biomass-based) products.
- Defining benefits, tradeoffs and concerns related to use of bio-based products, and
- Demonstrating results to encourage use by all.

## **10. Project Objectives:**

- Help NPS and industry develop options to reduce environmental degradation without decreasing visitations to Yellowstone NP or restricting snowmobile use.
- Support commercialization of biomass-based fuel and lubricants, reducing both dependence upon imported oil and impacts on the environment.
- Encourage the development, production and use of bio-based products within the region by identifying potential markets.
- Determine the impacts, benefits and concerns of using bio-based products in environmentally sensitive applications, including the promotion of an emissions test procedure that reflects real-world use.
- Initiate a cooperative working relationship regarding alternate fuels between government and private sectors.

## **11. Approach:**

The project will provide detailed data of developing products and will demonstrate alternate fuel options for reducing pollution, smoke, and health concerns caused by snowmobiles. (See Expanded Description and Major Milestones.)

## **12. Major Milestones:**

**Milestone 1:** June 1996. Project management, obtain and review test cycle approved by the industry, identify concerns from all participants, identify candidate fuels and lube oils

**Milestone 2:** July 1997. Conduct Laboratory Emissions Tests: Conduct emissions tests of alternate fuels and lube oils at SwRI using the ISMA test cycle. For two engines, samples will be collected on Criteria Emissions (NO<sub>x</sub>, HC, PM, HC, carbon dioxide (CO<sub>2</sub>), sulfates and select samples of air toxics (hydrocarbon speciation), ketones, aldehydes, and polycyclic aromatic hydrocarbons (PAH) to develop an emission factor (gm/kWh). Fuels and lubes tested include:

- a) Reference gasoline (EEE Clear) and conventional lube oil (baseline case)
- b) Gasohol (10% ethanol in gasoline) and conventional lube oil
- c) Gasoline and bio-based lube oil No. 1 (like CONOCO's Bio-Synthetic lube)
- d) Gasohol and bio-based lube oil No. 1 and



- e) Gasoline and bio-based and other lube oils (1 engine, mode 1 (wide-open throttle) only, Bombardier/Castrol biodegradable synthetic 2-stroke oil, and high PIB lube oil--Torco smokeless)

**Milestone 3:** Field Demonstration of Bio-based Options

- **Activity A:** November 1995 through March 1996. Conduct pilot demonstration using bio-based oil in NPS fleet.
- **Activity B:** Modify field demonstration based on emissions tests and previous years' experience. For each year, collect records on fuel and lube oil consumption, mileage, maintenance, etc. Coordinate use with ambient air monitoring.
- **Activity C:** Conduct additional field demonstrations using select options. November 1996 through March 1997, and November 1997 through March 1998, depending on funds
- **Activity D:** June-August 1998. Report results to Participants.
- **Activity E:** June-September 1998. Develop recommendations and final comparative analyses

**Milestone 4:** September 1998. Analyses, reporting and information dissemination.

**13. Accomplishments, Results, and Activities:**

The DOE project focuses on solving the problems at Yellowstone National Park and West Yellowstone. However, the results of this project will affect the industry and other countries.

A. As a result of the 1995/6 pilot demonstration, the Montana Department of Fish Wildlife and Parks now uses Castrol's (Rotax XPS) Biodegradable Synthetic Lubrication Oil in SkiDoo fleet snowmobiles. Laboratory emissions tests were completed in June 1997. Preliminary findings were discussed with industry and a number of potential users. The meetings were to help clarify the findings for potential users of the data. Several articles were written and distributed.

B. The effects of biomass-based fuels and lubes were studied under laboratory conditions. Alternative fuels and lubricants were tested in both fan-cooled and water-cooled snowmobile engines to determine effects on emissions, fuel consumption, and power. The following laboratory observations were made:

- Gasohol reduced HC (16 percent), CO (9 percent), and PM (25 percent) emissions, and slightly increased NO<sub>x</sub> emissions, while maintaining equivalent engine power, as compared to results with reference gasoline. The liquid-cooled engine was less sensitive to fuel changes than the fan-cooled engine. The rate of particulate matter produced was more than double the rate of the fan-cooled engine. Gasohol reduced CO (6 percent) and particulate matter (3 percent), but increased hydrocarbons (by about 5 percent). Tests were sensitive to changes in ambient air temperature and humidity.
- The aliphatic fuel, while increasing *total* hydrocarbon emissions, yielded the lowest ozone formation potential of the three fuels tested due to its low specific reactivity.
- Lubricant formulation affects PM emission rates. The high PIB Torco Smokeless lubricant created significantly less PM (70 percent lower than conventional lubes when gasohol is used as the fuel) than the three other lubricants tested. The biodegradable lubricants reduced carbon monoxide (by as much as 38 percent with the Conoco oil) and hydrocarbons, while increasing particulate matter.
- Particulate emission levels are influenced by lubrication rate, and may also be influenced by engine design. The fan-cooled engine had significantly higher spark plug seat temperatures and, by inference, cylinder temperatures, and substantially lower PM emissions, than the liquid-cooled engine.
- Toxic hydrocarbon species are present in snowmobile engine exhaust in similar proportions to those observed from other sources such as passenger cars.
- Benzene emissions were considerably reduced with the aliphatic fuel.

C. Laboratory results were presented at area meetings and through several articles. The lab report findings are being applied by private industry and individuals in the area -- both in Montana and a few in Wyoming. Results showed that alternative fuels and lubes reduced emissions and increased the market for fuel ethanol and biodegradable lubes as outlined below.

A number of field demonstrations were conducted by public and private fleets during the 1997/8 season. Gasohol could not be provided through the existing NPS contract for fuel with the Department of Defense. Fuel ethanol had to be donated if gasohol was to be used for the 1997/98 season. Storage of the fuel ethanol or blended gasohol also proved to be a challenge because no one had tankage for these fuels. The Renewable Fuels Association donated the fuel ethanol produced by Heartland Grain Fuels, Aberdeen SD, and the fuel was stored and delivered to NPS contractors by Allen Oil Company, Helena MT.

1. As a result of this demonstration, the Park Service at Yellowstone requested its next fuel supply agreement to provide only gasohol in place of gasoline for year-round use (about 220,000 gallons). The contractor was selected through their normal solicitation, and gasohol (E-10) became the only fuel for gasoline-powered NPS vehicles in Yellowstone starting June 1, 1998. AmFac, Yellowstone's primary concessionaire, is also planning to use gasohol in its winter fleet. The Yellowstone Park Service Stations (YPSS) are investigating the feasibility of offering gasohol to the public for the 1998/99 winter season. Conversion of these two concessionaires would change another 2.5 million gallons per year of gasoline to gasohol. Plans may be hampered by any changes to the underground tank replacement program now in progress, including the use of a different (E-10) fuel.

2. The private sector actively promoted the use of these products through news releases and paid radio announcements. By January 4, 1998, all West Yellowstone snowmobile and snowcoach operators voluntarily were using gasohol and environmentally preferred lubes. All service stations in West Yellowstone carried gasohol. Gasohol also was provided at service stations in Jackson and Cody, Wyoming.

3. Based on the work conducted at SwRI and information supplied by one of the West Yellowstone snowmobile rental operators, estimates were made of emission reductions achieved through the use of alternative fuel and lube. That operator used 225 sleds with an average engine displacement of 500cc.

His fleet used Polaris Synthetic Plus lube, which is assumed to have emissions similar to Rotax XPS Synthetic. His fleet traveled a total of 800,000 miles, consuming about 70,000 gallons of gasohol. We estimate that this fleet alone reduced hydrocarbon emissions in Montana and the Park by about 14.8 tons, carbon monoxide emissions by about 20.3 tons, and particulate matter (less than 10 microns in diameter) by about 324 pounds, compared to the use of conventional products. Actual field measurements may vary due to weather conditions. However, we would expect the percent reduction of emissions to be about the same. In other words, the use of gasohol and synthetic lube oil would reduce hydrocarbons by 16 to 25 percent, particulate by about 25 to 30 percent, and carbon monoxide by 9 to 20 percent, depending on engine technology.

D. As a result of the laboratory and field work, DEQ drafted text for a brochure (attached to this summary) on how to make snow machines environmentally friendly. The text was distributed by area snowmobilers to visitors, and incorporated with other rules for snowmobiling on their World Wide Web page. The brochure is being printed by Conoco. Polar Bear Productions and Conoco have teamed up to develop a cost-shared program for television that summarizes this work. The program is aimed at snowmobilers visiting in the Yellowstone area, and is planned for airing in the 1998/9 season.

E. Comments from EPA on the draft final laboratory report were received in May 1998. The final report includes analyses and recommendations as to the best methods to reduce the concerns with snowmobiles in Yellowstone National Park. A paper was presented in October 1997 at the Small Engine Technology Conference reporting these results. A test procedure was developed and validated by SwRI and the snowmobile industry. Results of this work were published in an SAE Paper. The findings and data in the DOE draft report were confirmed by this work and are being used by other agencies as they develop regulations on snowmobiles.

## **Follow-up Activities**

Old questions regarding emissions still remain, and new ones developed from this work. The overall understanding of snowmobile emissions would be enhanced with an expansion of the DOE project to provide additional data for snowmobilers, NPS, and EPA. Additional work should be done to investigate

noise, personal exposure to air toxics, and to develop other possible solutions to winter transportation problems.

A. A series of eight scientific studies (totaling about \$807,000) was developed to evaluate the questions remaining from laboratory investigations and field demonstrations. By September 28, 1998, all but two studies had been fully funded. This science program for the 1998/99 winter will develop more data on fuels, emissions, economics, and winter use (only \$22,800 of it will be from the Western Regional Bioenergy Program). These studies will be the basis for the Yellowstone winter use EIS, and results will be applied over the next 20 or more years.

B. This project also helped fuel the Green Gateway Corridors Project which promotes safety and the availability of environmentally friendly products at service stations along the highways leading to and from the Park. Conoco stations (and later others) will use environmentally friendly products and practices in the Park gateway corridors (Yellowstone, Grand Teton, Glacier, etc). This project was developed during the Greening of Yellowstone Workshop in May 1998, along with two others that follow.

1. As a result of discussions at the Workshop, Planet Electric will work with Gote Snowmobile Technologies, Clyde Park MT, in developing an electric snowmobile for use in Yellowstone area fleets. Testing of these sleds will occur during the 1998-1999 winter season.

2. Other meetings at the May Workshop resulted in development of a national student design competition for snowmobiles. The competition will be under the auspices of the Society of Automotive Engineers (Tony Androssi). The community of Jackson, Wyoming, will host the acceleration and hill climbing events. The emissions competition will be done in two parts--in-motion (Dr. Don Stedman and Dr. Gary Bishop of the University of Denver), and at idle (Wyoming DEQ). Other competitions still seeking sponsors include a cold-start event, an endurance competition, and a noise competition. Potential sponsors should contact Dr. Lori Fussel, 307-733-9745.

3. The International Snowmobile Manufacturers Association is working with the SAE to review and update the noise test for snowmobiles. Each manufacturer has a sound engineer on the task force in addition to two sound engineers from SAE. The task force is looking at modifying the current SAE test so that it can be used easily under field conditions.

### **Awards, Reports, Papers, Acknowledgments**

- U. S. Environmental Protection Agency EPA Region VIII. Outstanding Achievement Award to DEQ for Teamwork and Environmental Stewardship in Yellowstone National Park as exemplified by the Snowmobile and Truck in the Park Teams, August 27, 1996.
- Conoco President's Award to DEQ for the Environment, May 1996.
- Top Honors (international) DuPont Award to DEQ for the Environment and Safety.

White, Jeff J., James N. Carroll, Howard E. Haines. October 1997. **Emissions from Snowmobile Engines Using Bio-based Fuels and Lubricants**. Small Engine Technology Conference, JSAE 9734412, SAE 972108. Society of Automotive Engineers of Japan, Yokohama, Japan.

Wright, Christopher W., Jeff J. White. September 1998. **Development and Validation of a Snowmobile Engine Emission Test Procedure**. International Off-Highway & Powerplant Conference and Exposition, SAE 982017. Society of Automotive Engineers, Milwaukee, Wisconsin.

### **Future Activities and Technology Transfer Events**

- Develop additional funding for follow-up projects, request time extension
- Coordination of final report with airshed model

15. **Date Prepared:** May 4, 1995  
**Date Amended:** August 21, 1998

## **Make Your Snow Machine More Environmentally Friendly - Draft Text**

### **Making a Difference**

**All** snowmobile and snowcoach rental operators in West Yellowstone have agreed that gasohol is an environmentally friendly product to use. Most will use gasohol this winter to protect air and water quality in Yellowstone Park and vicinity. Most snowmobile rental operators in West Yellowstone also will be using synthetic lube oils shown to reduce pollution. The Park Service will use gasohol and a synthetic biodegradable lube in its snowmobiles in Yellowstone. The use of gasohol and synthetic lube oils by rental operators and the Park Service will reduce snowmobile carbon monoxide emissions by 9 to 38 percent, and particulate emissions by 24 to 55 percent, compared to previous years. Further, service stations in West Yellowstone, Montana, and Cody and Jackson, Wyoming have committed to making oxygenated fuel available to the general public for all private vehicles. Snowmobilers in the Yellowstone area are encouraging visiting snowmobilers to join the effort and use oxygenated fuels and synthetic low emission lube oils when in the area. This should reduce any potential health hazards, especially to children, pregnant women, older people, people with cardiovascular disease, and those with impaired lung function such as asthma sufferers.

#### **Checklist to Make Your Snow Machine More Environmentally Friendly**

- use proper jets, keep engines tuned and clutches adjusted properly for the elevation where machines operate
- use oxygenated fuels such as “gasohol” to reduce pollution
- use synthetic low-particulate lube oils to reduce particulates and smoke
- use synthetic biodegradable lube oils to reduce carbon monoxide
- check with your dealers, outfitters, and/or retailers for availability of these and similar products

For more detailed information and follow-up activities, see [www.deq.mt.gov/ppa/index.htm](http://www.deq.mt.gov/ppa/index.htm) (click on “Greening of Yellowstone, 2-stroke Emissions”), or contact Montana Department of Environmental Quality at 406-444-4643, or e-mail [hhaines@mt.gov](mailto:hhaines@mt.gov).

## **Background**

In recent years, the burgeoning popularity of snow machines in and around Yellowstone National Park has led to concerns about the possible environmental effects of this winter recreation. Winter use by snowmobilers in the park increased from 45,000 visitors in 1986 to about 85,000 in 1994, the most recent year of uninterrupted snowmobile use. The particular conditions in Yellowstone, including the dense, cold, often stable air, in combination with the specific emissions from snow machine engines, have the potential to produce unacceptable impacts to the environment.

## **Air Quality and Environmental Problems**

Both Park Service personnel and visitors have expressed concern about haze, carbon monoxide, and odors of exhaust in areas of heavy snow machine use in Yellowstone. These problems are especially noticeable along roads to Old Faithful. Emissions from snow machines include carbon monoxide, hydrocarbons, particulate material, and a variety of gases classified as “air toxics.” Poor air quality detracts from the quality of visitor experience and can be a health hazard.

## **Some Solutions**

Emissions from snowmobiles can be minimized by keeping the engines tuned properly for the elevation where they are operating. The high altitude of Yellowstone, ranging from 6,600 to 8,500 feet along the roads traveled by snow machines, requires carburetor jets with smaller orifices than would be used at lower elevation. Use of the smaller jets results in more complete fuel combustion. Installation of proper jets for higher elevation also improves engine performance, and snowmobile clutches should be adjusted to match performance. These adjustments usually must be made by a qualified mechanic. Proper clutch adjustment also reduces fuel use and emission of pollutants.

Another promising method for reducing emissions is the use of oxygenated fuels and specially formulated lube oils. The oxygenated fuel used in Montana is gasohol which consists of 10 percent ethanol and 90 percent conventional gasoline. Use of gasohol and other oxygenated fuels reduces emissions of most harmful pollutants from gasoline engines in both snowmobiles and snowcoaches.



Various manufacturers of low-emission 2-cycle oil combine various characteristics into their formulations. Testing funded by the Montana Department of Environmental Quality (DEQ) and others compared emission levels from a conventional petroleum-base lube oil to those from three oils formulated to improve performance and reduce emissions. These were: Conoco Bio-Synthetic 2-Cycle Engine Oil, which is highly biodegradable; Bombardier Rotax (Castrol) Formula XPS Synthetic Two-Stroke Oil (a synthetic biodegradable lube with solvent) which is biodegradable and produces lower particulate emissions; and TORCO Synthetic Smoke-Less 2-Cycle Oil, a fully synthetic lube oil that is low particulate but not biodegradable.

Test results show that the use of synthetic low-particulate oils significantly reduces pollution. Synthetic biodegradable lube oils reduced carbon monoxide, and probably would reduce any potential impacts to water quality. Snowmobilers should check with their dealers, outfitters, and/or retailers for availability of these products, which will become more available in the near future. For more detailed information on the use of ethanol blend in your machine, see Understanding Ethanol in **Snowmobile** magazine, October 1997.

**TABLE 6. POLARIS ENGINE--5-MODE CYCLE EMISSION TEST RESULTS**

| Fuel                     | Lubricant | Test ID | Emissions, g/kW-h |      |                   |      | BSFC,<br>kg/kW-h | Mode 1<br>kW |
|--------------------------|-----------|---------|-------------------|------|-------------------|------|------------------|--------------|
|                          |           |         | BSHC              | BSCO | BSNO <sub>x</sub> | BSPM |                  |              |
| Gasoline                 | ARCTIC    | A11-3   | 223               | 589  | 0.61              | 2.13 | 0.68             | 43.8         |
| Gasoline                 | ARCTIC    | A11-4   | 180               | 526  | 0.56              | 1.49 | 0.60             | 46.2         |
| Baseline Gasoline (mean) |           |         | 202               | 558  | 0.59              | 1.81 | 0.64             | 45.0         |
| Gasoline                 | ARCTIC    | RICH    | 241               | 635  | 0.42              | 2.31 | 0.72             | 38.9         |
| RICH/Baseline            |           |         | 120%              | 114% | 72%               | 128% | 113%             | 86%          |
| Gasoline                 | CONOCO    | A12     | 199               | 537  | 0.57              | 3.01 | 0.62             | 45.9         |
| A12/Baseline             |           |         | 99%               | 96%  | 97%               | 166% | 97%              | 102%         |
| Gasohol                  | ARCTIC    | A21     | 170               | 506  | 0.59              | 1.38 | 0.60             | 46.1         |
| A21/Baseline             |           |         | 84%               | 91%  | 100%              | 76%  | 93%              | 102%         |
| Gasohol                  | CONOCO    | A22-1   | 140               | 445  | 0.59              | 2.26 | 0.54             | 46.9         |
| A22-1/Baseline           |           |         | 69%               | 80%  | 100%              | 125% | 84%              | 104%         |
| Aliphatic                | ARCTIC    | A31-1   | 245               | 552  | 0.63              | 2.53 | 0.70             | 42.1         |
| Aliphatic                | ARCTIC    | A31-2   | 292               | 586  | 0.68              | 2.80 | 0.76             | 43.4         |
| Mean Aliphatic           |           |         | 269               | 569  | 0.66              | 2.67 | 0.73             | 42.8         |
| Aliphatic/Baseline       |           |         | 133%              | 102% | 112%              | 147% | 113%             | 95%          |

### TABLE 10. POLARIS ENGINE--5-MODE CYCLE SPECIATION RESULTS

| Fuel                         | Lubricant | Test ID | Emissions, g/kW-h |           |           |         |          |          | Ozone Potential g/kW-h | Specific Reactivity g O3/g HC |
|------------------------------|-----------|---------|-------------------|-----------|-----------|---------|----------|----------|------------------------|-------------------------------|
|                              |           |         | BSHC (FID)        | BSHC (GC) | 1,3-Buta- | Benzene | Formald. | Acetald. |                        |                               |
| Gasoline                     | ARCTIC    | A11-3   | 223               | 210       | 0.29      | 1.69    | 1.50     | 0.20     | 630                    | 3.00                          |
| Gasoline                     | CONOCO    | A12     | 199               | 188       | 0.30      | 1.49    | 1.01     | 0.12     | 568                    | 3.02                          |
| Gasohol                      | ARCTIC    | A21     | 170               | 172       | 0.31      | 1.52    | 1.58     | 1.11     | 532                    | 3.09                          |
| Gasohol/Gasoline (A21/A11-3) |           |         |                   |           |           |         |          |          | 84%                    | 103%                          |
| Gasohol                      | CONOCO    | A22-1   | 140               | 142       | 0.28      | 1.25    | 1.50     | 0.59     | 438                    | 3.08                          |
| Gasohol/Gasoline (A22-1/A12) |           |         |                   |           |           |         |          |          | 77%                    | 102%                          |
| Aliphatic                    | ARCTIC    | A31-1   | 245               | 220       | 0.38      | 0.46    | 1.86     | 0.26     | 493                    | 2.24                          |
| Aliphatic/Gasoline           |           |         |                   |           |           |         |          |          | 78%                    | 75%                           |

**TABLE 11. MODE 1 SPECIATION RESULTS WITH DIFFERENT LUBRICANTS**

| Fuel           | Lubricant | Test ID | Emissions, g/kW-h |           |           |         |          |          | Ozone Potential<br>g/kW-h | Specific Reactivity<br>g O3/g HC |
|----------------|-----------|---------|-------------------|-----------|-----------|---------|----------|----------|---------------------------|----------------------------------|
|                |           |         | BSHC (FID)        | BSHC (GC) | 1,3-Buta- | Benzene | Formald. | Acetald. |                           |                                  |
| Gasohol        | CASTROL   | A23     | 91                | 86        | 0.40      | 1.29    | 2.19     | 0.62     | 329                       | 3.83                             |
| Gasohol        | TORCO     | A24     | 97                | 92        | 0.29      | 1.13    | 2.12     | 0.65     | 335                       | 3.64                             |
| Gasohol        | CONOCO    | A22-2   | 91                | 86        | 0.32      | 1.11    | 2.10     | 0.70     | 321                       | 3.73                             |
| TORCO/CASTROL  |           |         |                   |           | 72%       | 88%     | 97%      | 105%     | 102%                      | 95%                              |
| CONOCO/CASTROL |           |         |                   |           | 80%       | 86%     | 96%      | 113%     | 98%                       | 98%                              |

**TABLE 12. ARCTIC CAT ENGINE--5-MODE CYCLE SPECIATION RESULTS**

| Snowmobile | Fuel               | Lubricant | Test ID | Emissions, g/kW-h |         |          |          | Ozone Potential<br>g/kW-h | Specific Reactivity<br>g O3/g HC |
|------------|--------------------|-----------|---------|-------------------|---------|----------|----------|---------------------------|----------------------------------|
|            |                    |           |         | 1,3-Buta-         | Benzene | Formald. | Acetald. |                           |                                  |
| Polaris    | Gasoline           | ARCTIC    | A11-3   | 0.29              | 1.69    | 1.50     | 0.20     | 630                       | 3.00                             |
| Arctic Cat | Gasoline           | ARCTIC    | W11-1   | 0.12              | 1.05    | 0.93     | 0.12     | 582                       | 2.98                             |
|            | Arctic Cat/Polaris |           |         | 41%               | 62%     | 62%      | 60%      | 92%                       |                                  |
| Polaris    | Gasohol            | ARCTIC    | A21     | 0.31              | 1.52    | 1.58     | 1.11     | 532                       | 3.09                             |

|                    |         |        |     |      |      |      |      |      |      |
|--------------------|---------|--------|-----|------|------|------|------|------|------|
| Arctic Cat         | Gasohol | ARCTIC | W21 | 0.14 | 1.13 | 1.18 | 0.80 | 621  | 2.84 |
| Arctic Cat/Polaris |         |        |     | 45%  | 74%  | 75%  | 72%  | 117% |      |

**TABLE 13. PARTICULATE PHASE POLYCYCLIC AROMATIC HYDROCARBON EMISSIONS**

| Compound               | Brake Specific Emissions, µg/kW-hr |       |     |     |             |     |     |
|------------------------|------------------------------------|-------|-----|-----|-------------|-----|-----|
|                        | Weighted Total                     |       |     |     | Mode 1 Only |     |     |
|                        | W11-1                              | A11-3 | A12 | A21 | A22-2       | A23 | A24 |
| Naphthalene            | 1                                  | 1     | 1   | 0   | 0           | 0   | 0   |
| Acenaphthylene         | 39                                 | 6     | 23  | 7   | 0           | 0   | 0   |
| Acenaphthene           | 4                                  | 0     | 1   | 1   | 0           | 0   | 0   |
| Fluorene               | 117                                | 82    | 118 | 30  | 3           | 1   | 0   |
| Phenanthrene           | 306                                | 205   | 270 | 95  | 10          | 3   | 4   |
| Anthracene             | 104                                | 51    | 80  | 30  | 3           | 1   | 1   |
| Fluoranthene           | 424                                | 581   | 562 | 203 | 20          | 9   | 7   |
| Pyrene                 | 724                                | 835   | 730 | 374 | 20          | 10  | 14  |
| Benzo(A)Anthracene     | 86                                 | 114   | 85  | 47  | 8           | 8   | 4   |
| Chrysene               | 68                                 | 65    | 46  | 32  | 7           | 7   | 4   |
| 1-Nitropyrene          | 2                                  | 3     | 0   | 2   | 0           | 1   | 0   |
| Benzo(B)fluoranthene   | 55                                 | 50    | 36  | 22  | 5           | 9   | 7   |
| Benzo(K)fluoranthene   | 54                                 | 41    | 29  | 17  | 4           | 7   | 6   |
| Benzo(E)pyrene         | 44                                 | 78    | 58  | 33  | 5           | 8   | 8   |
| Benzo(A)pyrene         | 75                                 | 109   | 83  | 41  | 6           | 9   | 8   |
| Indeno(1,2,3-CD)pyrene | 91                                 | 135   | 100 | 42  | 10          | 12  | 14  |
| Dibenz(A,H)anthracene  | 3                                  | 3     | 1   | 1   | 0           | 1   | 1   |

|                      |     |     |     |     |    |    |    |
|----------------------|-----|-----|-----|-----|----|----|----|
| Benzo(G,H,I)perylene | 138 | 597 | 328 | 300 | 30 | 33 | 45 |
|----------------------|-----|-----|-----|-----|----|----|----|

## TABLE 15. AMMONIA EMISSIONS

| Fuel                                      | Lubricant | Test ID | NH3 Emissions, g/kW-h |        |        |        |         |            |
|---|-----------|---------|-----------------------|--------|--------|--------|---------|------------|
|   |           |         | Mode 1                | Mode 2 | Mode 3 | Mode 4 | Mode 5* | Wtd. Total |
| Polaris                                   |           |         |                       |        |        |        |         |            |
| Gasoline                                  | ARCTIC    | A11-3   | 0.02                  | 0.15   | 0.14   | 0.11   |         | 0.10       |
| Gasohol                                   | CONOCO    | A22     | 0.01                  | 0.07   | 0.08   | 0.03   |         | 0.05       |
| * Idle mode - g/kW-h value not meaningful |           |         |                       |        |        |        |         |            |